unique to satellite systems, and is particularly aggravated at the higher frequencies. Also, symmetry applies in these systems. Statistical assumptions made and procedures developed for terrestrial systems, and for satellite systems below 10 GHz, may not be adequate for the applications to which this Handbook is directed.

Some sort of availability allocation is necessary, since most of the propagation data and procedures for applying them are oriented towards single path availability. The composite availability calculations involved are similar to multiple and redundant part reliability calculations. Each application will involve its own special considerations in the allocation process. Often, a worst case philosophy is applied in an attempt to simplify the problem. The following factors are relevant:

- One end (terminal location) often has considerably worse rain statistics than the other.
- Satellite systems are limited in downlink power; uplink power margin at the earth terminal is more readily obtainable.*
- Uplink and downlink effects are quantitatively similar except for widely separated uplink/downlink frequencies (e.g., 30/20, 43/20), where attenuation factors in particular can differ substantially.
- The uplink and downlink connecting to a given earth terminal have highly correlated propagation outage statistics.
- The propagation effects on paths between the satellite and two different earth terminals are uncorrelated.

Because of the variety of system concepts and frequency bands possible, general rules for allocation of availability cannot be given. The following may be of help in many cases of interest:

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*A very important exception involves mobile or portable terminals.

- In a one-way (simplex) system, availability can be suballocated or split between the up and downlink with considerable freedom.

  Frequently, however, the downlink is the dominant (weaker) link. In other words, the working assumption is that the uplink non-availability is an order of magnitude smaller than the downlink's.

- For a two-way (duplex) system, one of the following simplifications may be applied:.

  - One end has much worse rain statistics than the other. Then, this duplex circuit can be treated as two simplex circuits with the majority of the outages on that end. On each of these simplex circuits, either the uplink <u>or</u> the downlink, whichever is worse, dominates the availability.

  - Assume initially that uplink margin is liberally available. The duplex link availability is then determined by the composite availability of <u>both</u> downlinks (or, the circuit outage time is the sum of the outages of each of the two downlinks).

Because the designer is forced by the procedure to iterate the design, errors introduced by simplifying assumptions made during the availability suballocation phase are corrected when performance verification analyses are made. For example, suppose the initial downlink design parameters were selected under the assumption that ample uplink margin exists, and that the uplink parameters were chosen to be as good as possible within economic constraints. In the final performance computation, the slightly less than perfect availability of the uplink is factored into the overall availability. Any shortfall relative to requirements can then be met by a small adjustment to the downlink parameters, in the next iteration of the design.

7.3.3 Summary of Procedures for Application of Propagation Data

The system design procedure presented here is based on criteria that take the form of discrete cumulative probability distribution functions of performance. In practice, three, two, or just one point on this distribution are given, for example, 99.9% probability that the baseband signal to noise ratio exceeds 20 dB. The worst (lowest probability) point of this set is usually considered to be the outage point or the non-availability threshold. In addition, a statement might be made about the time characteristics of the outage events, for example, the maximum acceptable value for the average duration. These criteria are usually for the baseband (e.g., voice channel) noise performance, or for the digital channel performance (e.g., error rate). The steps necessary to go from this set of requirements and propagation statistics to a system design are (see Figure 7.3-1):

<u>INITIAL PHASE</u>

1) Establish system performance requirements (discrete distribution of baseband/digital performance)

2) Apply modulation equations to convert system performance requirements to discrete distribution of the received composite CNR

3) Prepare initial design with parameters sized according to free space propagation conditions (apply power budget equations).

<u>DESIGN SYNTHESIS AND TRADEOFF PHASE</u>

4) Employ

   a) Composite CNR distribution from step 2

   b) System Architecture

   c) Multiple Access Equations

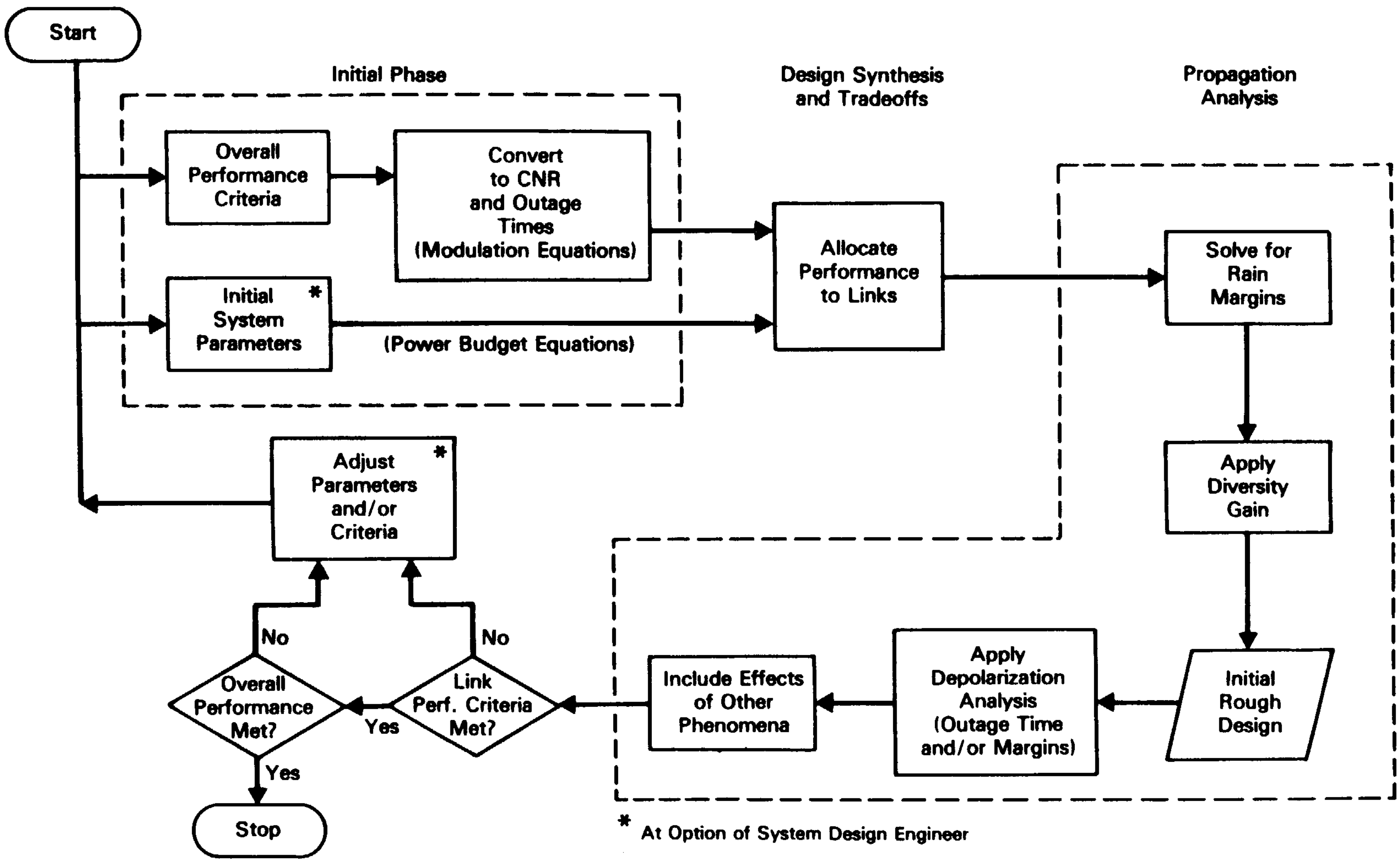

Figure 7.3-1. System Design Process

d) Availability sub-allocation philosophy to develop distribution functions for CNR on each path.

PROPAGATION ANALYSIS AND ITERATION PHASE

5) Compute rain margins, as reduced by diversity gain, for each path.

6) Adjust system parameters according to margins given by step 5. This gives a preliminary design at the feasibility concept level.

7) Apply depolarization analysis to adjust margins and/or increase the outage time values (% of time for the worst-performance level of the distributions).

8) Consider other propagation effects, adding margin to design as necessary.

9) Adjust system parameters to include all additive margins. Analyze system performance, first at the path level, then at the end-to-end performance level.

10) If performance meets requirements closely, stop. Otherwise, adjust design and repeat analysis. If design cannot be made to meet requirements, consider changing requirements.

These steps will be considered in more detail in the remainder of this chapter. The most difficult step is 4 above. It is not possible to define a step-by-step "cookbook" procedure for this phase of the design process.

As indicated above, these steps may be grouped into three major phases. It is in the third phase that propagation phenomena and data are explicitly considered. Since the emphasis of this Handbook is propagation, a detailed exposition of the first two phases is not appropriate. However, some discussion is required because both performance criteria and the system engineering are profoundly influenced by the pronounced propagation effects which apply above 10 GHz.

7.3.4 Specifics of Applications Initial Phase - Performance Specification of Digital and Analog Systems

The initial phase contains three steps:

1) performance requirements

2) conversion to received CNR requirement

3) initial design choices

Two examples will be used to illustrate the design procedure. The first step, to specify performance requirements, is now carried out for the examples. Additional information will be given for the systems in the example as they are developed further.

EXAMPLE 1 (Digital transmission system)

Requirement: One-way bit error rate of 10^{-6} or better for at least 80% of the time, and 10^{-4} or worse for a maximum of 1% of the time.

EXAMPLE 2 (Analog, duplex telephone trunking system)

Requirement: No more than 10,000 pW0p for at least 80% of the worst month, and no more than 100,000 pW0p, except for 0.3% of the time or less. (More than 500,000 pW0p is outage condition.)

The second and third steps are performed in parallel. Conversion from the basic performance criteria to receiver CNR requirements involves application of modulation equations. To apply the equations, the type of modulation* and other system parameters such as total link capacity need to have been selected. For the above two examples:

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*"Modulation" is used in a generic sense here, to include coding, baseband processing, and the like.

1) The digital system is considered to operate at a link data rate of 40 Mbps, employing quaternary phase shift keying (QPSK) and Rate 3/4 convolutional encoding with Viterbi decoding. This combination is assumed to operate with an E_b/N_o of 10.3 dB for a BER of 10^{-4}, and 12 dB for 10^{-6}. The values of C/kT required are 86.3 and 88 dB-Hz, respectively. Because of the rate 3/4 coding, the symbol rate is 4/3 x 40 = 53.5 Ms/s and the CNR values in the symbol rate bandwidth are 9 and 10.7 dB for 10^{-4} and 10^{-6} BER, respectively.

2) The analog system is assumed to use FDM-FM with 120 channels and CCIR pre-emphasis characteristics. The following is a simplified version of the FM modulation performance equation (see Section 7.2.1.3):

$$(C/kT)_{dB} = 125.8 - 20 \log (\Delta f/f_{ch}) - 10 \log (pW0p)$$

From this, and the typical parameters $\Delta f/f_{ch} = 1.22$, the required values of C/kT are:

pW0p	C/kT	%
10,000	84.1	80
100,000	74.1	99.7
500,000	67.1	N/A (defines outage)

Note however that the FM equation only applies above "threshold." The threshold values of C/kT must also be determined. Since this system has a bandwidth of about 62 dB-Hz, the threshold values of C/kT and the threshold C/kTB are related:

$$(C/kTB)_{dB} = C/kT - 62$$

Thus, if this system is implemented with a conventional FM receiver of 12 dB C/kTB threshold, a C/kT of 74 dB will be at threshold, and this becomes the outage point. With an extended threshold demodulator (6 dB threshold), the 500,000 pW0p outage noise level and the demodulator threshold occur at about the same point, which is desirable.

To complete the first phase of design, it remains to select initial values, ranges, or limits of system parameters. Many of these may be implied by overall system requirements, such as coverage area or total number of channels. Others may be constrained by cost considerations or achievable levels of hardware performance. The primary parameters that must all eventually be specified are the frequencies of operation, and the receive and transmit antenna gain, transmitted power, and receiver noise temperature of both the satellite and the earth terminal. We start by specifying as many of these as possible. In the subsequent design synthesis and trade-off phase, the parameter values are adjusted for consistency and the missing parameters are determined.

The initial parameters assumed for the digital example are the following:.

1) 12 GHz downlink, 14 GHz uplink
2) 3-meter earth terminal antenna, if possible, but no greater than 5 meters in any case
3) Satellite EIRP (equivalent isotropic radiated power, power times gain) on the order of 40 dBW
4) Ground terminal noise temperature no less than 300K
5) Satellite antenna receive gain - 33 dBi
6) Satellite receiver noise temperature - 1000 K.

For the analog example, we start with the following parameter values:

1) 30 GHz uplink, 20 GHz downlink
2) Ground terminal figure of merit (G/T: ratio of antenna gain over noise temperature) = 40 dB/K
3) Earth terminal receiver noise temperature = 200 K
4) Satellite antenna transmit gain = 36 dBi

5) Satellite antenna receive gain = 33 dBi

6) Satellite figure of merit (G/T) = 3 dB/K.

7.3.5 Design Synthesis and Tradeoff Phase

A general method of translating overall performance objectives into individual link objectives does not exist at this time for satellite systems operating above 10 GHz. Techniques have been developed for line-of-sight systems (Parker-1977 and GTE-1972), and satellite systems at lower frequencies (CSC-1971), but these have limited application in the present case. We present here some design tools that have been used in millimeter-wave system design. They include rules-of-thumb and simplifications that often apply, and more detailed procedures useful when the simplifying assumptions cannot be made.

At this point in the design procedure we have two functionally related parameters: a required composite C/N value, and the percentage of time for which this C/N applies. There may be several points of this function (the cumulative probability distribution function of C/N) specified. At some small percentage of time, the system is considered to be unavailable. At some larger percentage of time, a form of "degraded" operation might be defined, corresponding to a higher C/N value than the outage C/N. The present problem is one of assigning to each link of the system values of C/N and corresponding time percentages for which the values must be exceeded. Practically, this usually reduces to allocating outage time or availabilities among the links comprising the system, and allocating C/N values to the links in a way that is both compatible with the link outage time allocation, and achieves the required overall system performance.

7.3.5.1 Suballocation of Outages and Signal-to-Noise Ratio. One important element in this phase is the sub-allocation of outages. We have a specification on the permitted outage time for a service or circuit, which comprises 2, 4, or perhaps more links. It is clear that in general

$$\begin{matrix}\text{Outage} \\ \text{total}\end{matrix} = \sum \text{link outages} + \begin{pmatrix}\text{jointly} \\ \text{determined} \\ \text{outages}\end{pmatrix} \qquad (7.3\text{-}1)$$

The definitions of link outages are usually obvious once the system architecture has been defined. If the permitted total outage time is small (<1%), the jointly determined outages are extremely small and can be ignored. For example, if $(S/N)_{composite} < 10$ dB is an outage, then for a bent pipe repeater either $(S/N)_{up} < 10$ dB or $(S/N)_{down} < 10$ dB would constitute link outage events. Now, a variety of combinations (e.g., $(S/N)_{up} = 13$ dB and $(S/N)_{down} < 13$.dB) can also result in an outage condition. However, assuming uncorrelated statistics and a small percentage of time criterion, these joint contributions can be ignored with only slight error, since they are very small. Therefore it is reasonable for the initial design, even with bent pipe repeaters, to suballocate the total outage time to up- and downlinks according to the rule

$$\begin{pmatrix}\text{total} \\ \text{outage} \\ \text{time}\end{pmatrix} = \begin{pmatrix}\text{uplink} \\ \text{outage} \\ \text{time}\end{pmatrix} + \begin{pmatrix}\text{downlink} \\ \text{outage} \\ \text{time}\end{pmatrix} \qquad (7.3\text{-}2)$$

Using this outage time suballocation is particularly appropriate in digital systems where only a few dB separate nominal and barely acceptable performance. The nominal performance <u>analyses</u> (not syntheses) are performed in iterations subsequent to the initial design. These performance analyses must not be neglected, however, since a system design that meets a particular outage or availability criterion does not necessarily meet its other performance criteria (e.g., nominal performance). This is particularly important in analog systems where there can be a wide gap between what is considered an outage and what is required most of the time. Since it appears that most satellite systems being designed for above 10

GHz are digital, this difficulty is perhaps academic. In practice, the use of availability alone, or in conjunction with outage duration characteristics, is prevalent in the design of such systems.

In Table 7.3-1, we give the simplifying rules of thumb which may usually be employed for suballocation of outage time, T_{OUT}. In the duplex case, the exact value of T_{OUT} relative to its upper and lower bounds depends on the type of repeater and on the joint statistics of outage (i.e., the correlations between outages). The lower bound will apply if a perfect correlation of outages exists on the up- and downlink to a single terminal.

In general, the allocation of carrier-to-noise ratios among the several links is a more difficult problem. For the case of a bent-pipe repeater used for simplex service, the composite carrier-to-noise ratio $(C/N)_C$ for the circuit is given by

$$(C/N)_C = \left[(C/N)_U^{-1} + (C/N)_D^{-1} \right]^{-1} \qquad (7.3\text{-}3)$$

where $(C/N)_U$ and $(C/N)_D$ are the individual carrier-to-noise ratios on the uplink and downlink, respectively. Figure 7.3-2 illustrates the trade-off between uplink and downlink C/N defined by the equation. The combination of C/N values for a digital circuit through a processing (demodulating- remodulating) satellite repeater is different. In that case, it is the <u>errors</u> on the uplink and downlink rather than the noise power that are added. The C/N trade-off curve for a regenerative repeater would be similar to that in Figure 7.3-2, but with a sharper ""knee'' because of the high sensitivity of error probability to C/N.

Curves such as Figure 7.3-2 allow convenient selection of uplink and downlink C/N values, but in the absence of propagation statistics, there are no other criteria for selection. At the first

Table 7.3-1. Outage Time Allocation

Allocation Relations:

Simplex Circuit Outage

$$T_{OUT} = T_{AS} + T_{SB}$$

Duplex Circuit Outage Bounds

$$T_{AS} + T_{SB} + T_{BS} + T_{SA} \geq T_{OUT} \geq \text{Larger of} \left\{ \begin{array}{c} (T_{AS} + T_{SB}) \\ \text{or} \\ (T_{BS} + T_{SA}) \end{array} \right\}$$

Definition of Terms:

Total Outage Time	:	T_{OUT}
Uplink outage, Terminal A to Satellite	:	T_{AS}
Downlink outage, Satellite to Terminal B	:	T_{SB}
Uplink outage, Terminal B to Satellite	:	T_{BS}
Downlink outage, Satellite to Terminal A	:	T_{SA}

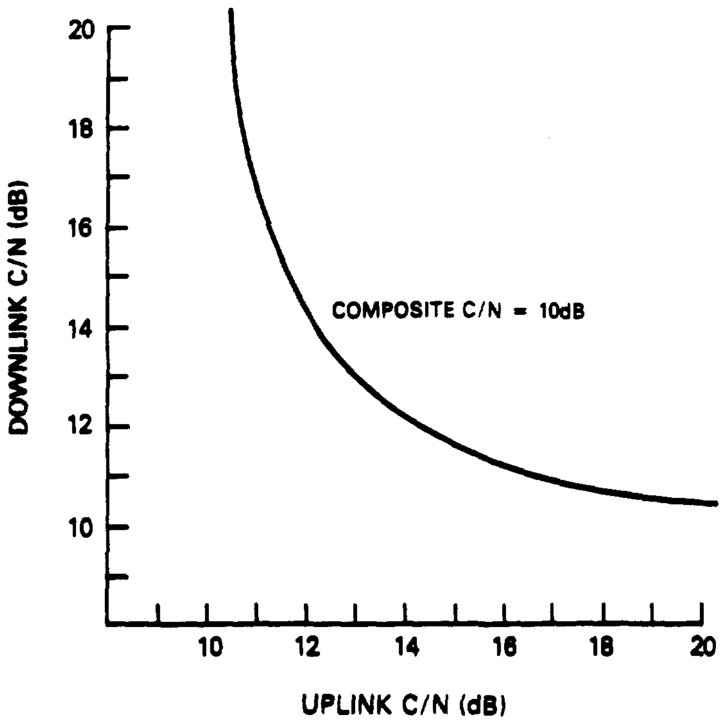

Figure 7.3-2. Uplink and Downlink Carrier-to-Noise Ratio (C/N) Trade-Off

iteration of the design synthesis phase, the selection is somewhat arbitrary. It will be refined in subsequent iterations. A good starting point may be equal C/N on both links. In this case, the link C/N must be 3 dB greater than the composite C/N. If allowed by system architecture, the uplink may be assigned a C/N value several dB more than that of the downlink because resources for achieving a high C/N (e.g., high-power amplifiers) are more readily available on the ground.

7.3.5.2 Power Budget Equation. The power budget equation relates the values of C/N or C/kT for individual uplinks or downlinks to physical system parameters. It defines the trade-offs possible between system components performance levels and is the basis of the current phase of system design. In decibel form, the downlink power budget equation is:.

$$C/N = P_t + G_t + G_r - L_{fs} - L_l - L_{rain} - 10 \log_{10} [kB (T_r + T_{sky})] \tag{7.3-4}$$

where:

P_t	=	satellite transmitter power, dBW
G_t	=	satellite antenna gain, dBi
G_r	=	ground receiving terminal antenna gain, dBi
L_{fs}	=	free space path loss, dB
L_l	=	attenuation losses which are constant, especially gaseous absorption, dB
L_{rain}	=	attenuation from rain, dB
k	=	Boltzmann's constant, 1.38×10^{-23} J/K
		($10 \log_{10} k = -228\ 6$ dB-K^{-1}-Hz^{-1})
B	=	bandwidth, Hz
T_r	=	receiving terminal noise temperature, K
T_{sky}	=	sky noise temperature, K

To calculate C/kT, the bandwidth B is simply left out of the equation. The equation for the uplink is the same except the satellite and earth terminal parameters are interchanged and T_{sky} is replaced with T_{earth}, the satellite antenna noise temperature increase due to the earth (discussed in Section 6.8.5). In these first phase iterations, one assumes L_{rain}=0dB, L_l=0dB, T_{sky}=0 K or some small clear air value. Note that ($P_t + G_t$) is the satellite EIRP, and that (G_r - 10 log T_r) is often given as a single parameter, the terminal's Figure of Merit or G/T.

7.3.5.3 Further Development of Design Examples. For the digital system example, the following assumptions are made:

1) The system will be assumed to operate in a simplex (one-way) mode for purpose of availability calculation (the necessary acknowledgments of data are assumed to occur at much lower data rates, therefore much higher availability).

2) TDMA is assumed. Therefore power sharing in the repeater is not a problem.

3) For initial system design, we will assign the same carrier-to-noise ratio to both the uplink and the downlink.

4) Nominal (long term) propagation characteristics will be assumed to apply, on the average, on both up and downlinks at the same times. Outage level fades in up and down directions will be assumed uncorrelated.

5) No terminal diversity will be employed.

We now apply the power budget equation to the downlink for the digital example. From the initial system parameters given in Section 7.3.4, we have

- Satellite EIRP = $P_t G_t$ = 40 dBW

- Earth terminal antenna receive gain = G_r

  = 18.2 + 20 log (freq.-GHz) + 20 log (diam.-m)

  = 18.2 + 20 log (12) + 20 log (3) = 49.3 dBi

- Bandwidth = symbol rate = 53.5×10^6

- Free space loss = L_{fs}

  = 92.4 + 20 log (range-km) + 20 log (freq.-GHz)

  = 92.4 + 20 log (35,780) + 20 log (12) = 205.1

The value of composite C/N used for the nominal (clear sky) condition will be that which must be exceeded at least 80% of the time, or 10.7dB. From assumption 3) above and the C/N allocation formula of Section 7.3.5.1, we select downlink C/N = 13.7 dB.

Substituting into the power budget equation, we find the required ground terminal noise temperature:

$$13.7 = 40 + 49.3 - 205.1 + 228.6 - 10 \log_{10} (53.5X10^6) -10 \log_{10} T_r$$

$$T_r = 152 \text{ K}$$

We note that this violates the minimum value restriction of 300 K assumed at the outset. Suppose we determine from spacecraft design considerations that it is possible to double the output power of the satellite. Doing this, we have the compatible initial values,

- $T_r = 300$ K
- $G_t + P_t = 43$dB

For the <u>uplink</u> in the <u>digital</u> example, we note from the initial parameter values assumed in Section 7.3.4 that everything is specified except ground terminal transmit power. We now use the power budget to find what value is required. First, we compute

- Free space loss for 14 GHz downlink = L_{fs} = 206.4 dB
- Ground terminal transmit gain = 50.6 dBi

The power budget equation, again assuming a link C/N of 13.7dB is required, gives the following

$$13.7 = P_t + 50.6 + 33 - 206.4 + 228.6 - 77.3 - 30$$

$$P_t = 15.2 \text{ dBW (approx. 30W)}$$

For the <u>analog</u> system example, we will proceed on the following assumptions:

1) Initial system sizing will assume equal carrier-to-noise density on the uplink and downlink. A better allocation for the duplex link, which cannot be made at this time, would be such that both the uplink and downlink at a given terminal reach the outage

threshold simultaneously (since there is no need to be capable of transmitting when one cannot receive).

2) Outage time will be split evenly between uplink and downlink.

3) Dual site diversity will be used if necessary to enhance availability on the downlink. We assume uplink diversity will not be necessary.

For the <u>downlink</u>, at 20 GHz, we have

- Free space loss = L_{fs} = 209.5 dB
- Nominal (clear air) C/kT required is 3dB more than the composite C/kT that must be exceeded at least 80% of the time. Thus, downlink C/kT = 87.1 dB.
- From Section 7.3.4, ground terminal G/T = 40 dB/K and satellite transmit gain = 36 dB.

We use the power budget equation to find the missing parameter, the satellite transmitted power P_t.

$$C/kT = P_t + G_t + G_r - L_{fs} - 10\ \log_{10}K$$

$$87.1 = P_t + 36 + 40 - 209.5 + 228.6$$

$$P_t = -8.0 \text{ dBW}$$

The 30 GHz <u>uplink</u> power budget requires the ground terminal transmit gain, which is 20 log(30/20) = 3.5 dB greater than the receive gain. The receive gain is found from the specified G/T (40dB) and noise temperature (200K) to be 40 + 23 = 63 dBi so the transmit gain is 66.5 dBi. Other parameters are

- Satellite G/T = 3 dB
- Free space loss = L_{fs} = 213 dB

We again solve for the required ground terminal transmit power:

$$87.1 = P_t + 66.5 + 3 - 213 + 228.6$$

$$P_t = 2 \text{ dBW}$$

It should be evident by now that, even prior to explicitly incorporating the various propagation elements, the system design process involves an iterative and interactive series of choices of parameter values. Each choice must be tempered by pragmatic considerations. There are in the above examples numerous unstated assumptions. For example, for the 12/14 GHz digital system, the earth terminal antenna diameter of about 3 meters is appropriate for a direct user-to-user application. Subsequent tradeoffs might influence a change to, say, 5 meters at most. It is not feasible, nor appropriate, to set down all of these system engineering considerations in this Handbook.

7.3.6 Propagation Analysis and Iterations Phase

7.3.6.1 Compute Rain Margin (less diversity gain) and Adjust System Parameters Accordingly. The rain margin is the increase in system transmission parameters (such as power or gain) needed to offset the attenuation caused by rain and other precipitation. Note that since precipitation also increases the effective noise temperature on downlink paths, the margin should include this effect as well. If the system employs diversity (particularly, but not exclusively, space diversity), there is an effective "diversity gain" which can be obtained. This diversity gain can be subtracted from the rain margin. These calculations are described in detail in Chapter 6 for rain and section 7.4 for diversity. The (possibly adjusted) rain margins must be applied on the up and downlinks in accordance with the performance suballocation decisions made in the previous phase. Once again, this is best illustrated through the examples.

We address the digital system example first. We will assume no measured attenuation or rain rate statistics are available, and will use the analytic estimation technique of Figure 6.3-1 (the Global Model). The location of the ground terminal is in climate region D3 at 35° N latitude and sea level, and the path elevation angle is 20°.

We are interested in the attenuation at 12 and 14 GHz exceeded 0.5% of the time. For this case, we calculate the horizontal projection distance of the path to be 9.9 km. The point rain rate exceeded in region D3 for 0.5% of the time is 7.8 mm/hr. The attenuation values exceeded for this time are predicted at 2.9 dB for 12 GHz and 4 dB for 14 GHz. The composite C/N for the circuit can be less than 9 dB for 1% of the time or less. Using an equal allocation philosophy, the carrier-to-noise ratio not exceeded on either link for 0.5% of the time should be 12 dB. With the current initial parameter values, the downlink clear air C/N is 13.7 dB. The rain attenuation expected would drop this to 9.7 dB, so at least 2.3 dB of downlink rain margin is needed. In a similar manner the required uplink margin is found to be 1.2 dB. The uplink margin could easily be provided by increasing the ground terminal transmitter power. The downlink margin can be gained either through an increase in satellite EIRP or ground station G/T. Rather than attempting to again increase the satellite EIRP, we shall exercise our option for 5-meter ground station antennas, which provides 4.4 dB more gain. (Note that ground stations located in drier climates may meet the availability requirements with 3-meter antennas.) Since a given ground terminal will presumably be used for transmitting as well as receiving, the antenna size increase also increases the ground station EIRP by 4.4 dB, providing more than ample uplink margin without increasing the transmitter power.

For the analog example, assume the same ground station location and path elevation angle. The outage time percentage of interest in this case is 0.15% for each link. The attenuation exceedance curves given by the computation of Figure 6.3-1 are shown in Figure 7.3-3. On the downlink, the attenuation exceeded for 0.15% of the time is 17.2 dB. From Figure 7.4-4, we see that up to 12 dB of diversity gain may be obtained at large separations. Here, we will assume that 10 dB can be achieved, so the attenuation exceeded is effectively 7.2 dB. Accompanying 7.2 dB of attenuation, there is (by Section 6.7.4) a sky noise increase of 220K. The noise temperature of the ground station (200K in clear air) increases by this amount, so the downlink C/N is reduced by a total of 10.4 dB. Recall that the composite C/N was allowed to be 10 dB worse than the nominal value for 0.3% of the time. Thus, provided we can limit the uplink degradation to less than 10 dB for at least 0.15% of the time, the downlink is nearly sufficient as is. We shall increase the satellite transmitted power by 2 dB to -6 dBW to guarantee its adequacy.

We can now determine how many 120 channel trunks may share the satellite repeater passband. Given that FDMA requires that the power amplifier be "backed off" from saturation for intermodulation noise reduction, and that solid state transmitter technology is limited to a few watts, we may decide that about 8 trunk-paths should be established per transponder channel. Following established practice for lower frequencies, these transponder channels will be 35 or 40 MHz wide.

For the 30 GHz uplink, Figure 7.3-3 shows that the attenuation value exceeded 0.15% of the time is 38.2 dB. Recall that under clear air conditions, a 2 dBW ground terminal transmitter yielded C/kT = 87.1 dB on the uplink. For C/kT = 77.1 dB with 38.2 dB of rain attenuation, the transmitter power would need to be increased to 30.2 dBW, or more than 1 kW. Considering the losses in transmitter output components and waveguide runs, this may require a power tube of several kilowatts, which is not now technologically feasible at 30 GHz. To provide the required uplink margin, then, either the satellite G/T must be drastically increased, or we must abandon our original assumption of no uplink diversity. We choose the diversity route as the more feasible. (Uplink diversity presents a technological problem of its own: the switchover of uplink transmissions between diversity sites is more difficult and potentially more disruptive to circuit integrity than diversity switching of downlink signals.) See Section 7.4 for a more detailed discussion of diversity problems.

Let us assume that 100W or 20 dBW of output power is readily achievable in the ground station. This means that the effective attenuation exceeded for 0.15% of the time cannot exceed 28 dB. This would require a diversity gain of at least 10.2 dB. Alternately, we may specify a diversity advantage (see Section 7.4.1). Figure 7.3-3 indicates that an attenuation of 28 dB is exceeded for about 0.3% of the time on the 30 GHz link. The required diversity advantage is therefore 2, which most available data (Engelbrecht-1979 and Hogg and Chu-1975) indicates is easily obtained. With some foresight, we will stipulate that 13 dB of diversity gain is required for the uplink (or the diversity advantage must be 2.3). See Figure 7.4-1 for definitions of diversity gain and diversity advantage.

7.3.6.2 Apply Depolarization Analysis. The transmission of two orthogonally polarized signals from one satellite is employed to double the spectrum utilization by frequency reuse. Not every system, of course, will need to employ this technique, in view of the additional complexity and the added potential contribution to propagation caused outages.

The term "depolarization" is commonly employed to designate the reduction in cross-polarization discrimination seen at the receiving location under some propagation conditions. When this occurs, each of the two received channels (polarizations) contains an interference signal from the other polarization. Therefore, this signal is similar to interference which may occur from other satellites, terrestrial systems, or other beams of the same satellite.

Depolarization is caused by rain, as well as by ice layers, in the troposphere. The rain can cause strong depolarization events, in which the cross-polarization discrimination drops to 20 or 15 dB. Ice depolarization is quantitatively milder, but appears to occur more often. It is therefore convenient to treat two cases of depolarization effects, strong and weak.

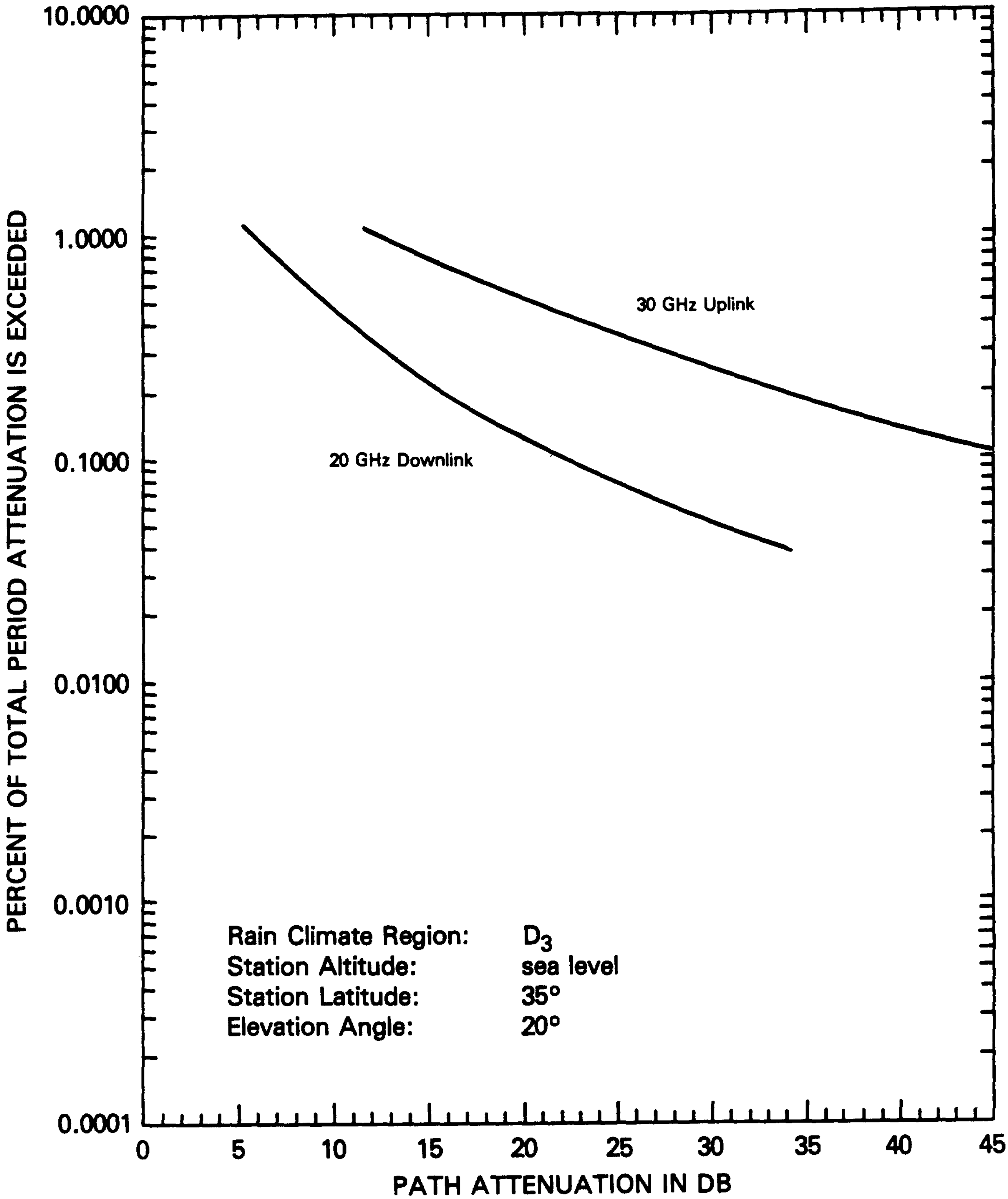

Figure 7.3-3. Analytic Estimate of Attenuation for 20 and 30 GHz Links of Example

Strong depolarization events should be correlated with deep attenuation events, since both stem from the same physical cause, namely rain. Both the deep attenuation fades and the strong depolarization intervals can cause outages. In order to perform a composite outage analysis, it is convenient to have joint statistical data, for example in the form introduced by Arnold, et. al. (1979). In Figure 7.3-4, we show a hypothetical version of such a joint outage plot. The parameter on the curves represents the threshold value of depolarization above* which the given system is inoperable, i.e., an outage exists. It can be seen that there may be many combinations of attenuation and depolarization that will result in any given probability of outage. Typically, the threshold depolarization is not an independent variable, but is fixed by the modulation parameters. Then, it can be immediately determined whether the previously computed rain margin is sufficient for the desired system availability.

In most cases, such joint statistics are not available. Section 6.6 presents methods for prediction of depolarization statistics, including functional relationships between attenuation and depolarization statistics. Using these prediction methods, it is possible to approximate curves like those in Figure 7.3-4, though the exact shape of each curve will not be mathematically precise. For example, the curve for "percent of time attenuation or depolarization exceeded" for the depolarization parameter equal to -10 dB is essentially the same as the attenuation versus percent exceeded curve alone (since depolarization is effectively "never" so large). For intermediate values of the depolarization parameter such as -25 dB, the appropriate curve is horizontally asymptotic to the percentage of time that depolarization alone exceeds the percentage. Each such horizontal asymptote then smoothly curves

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*Here depolarization in dB is given a minus sign so that the term "exceeded" can correctly apply.

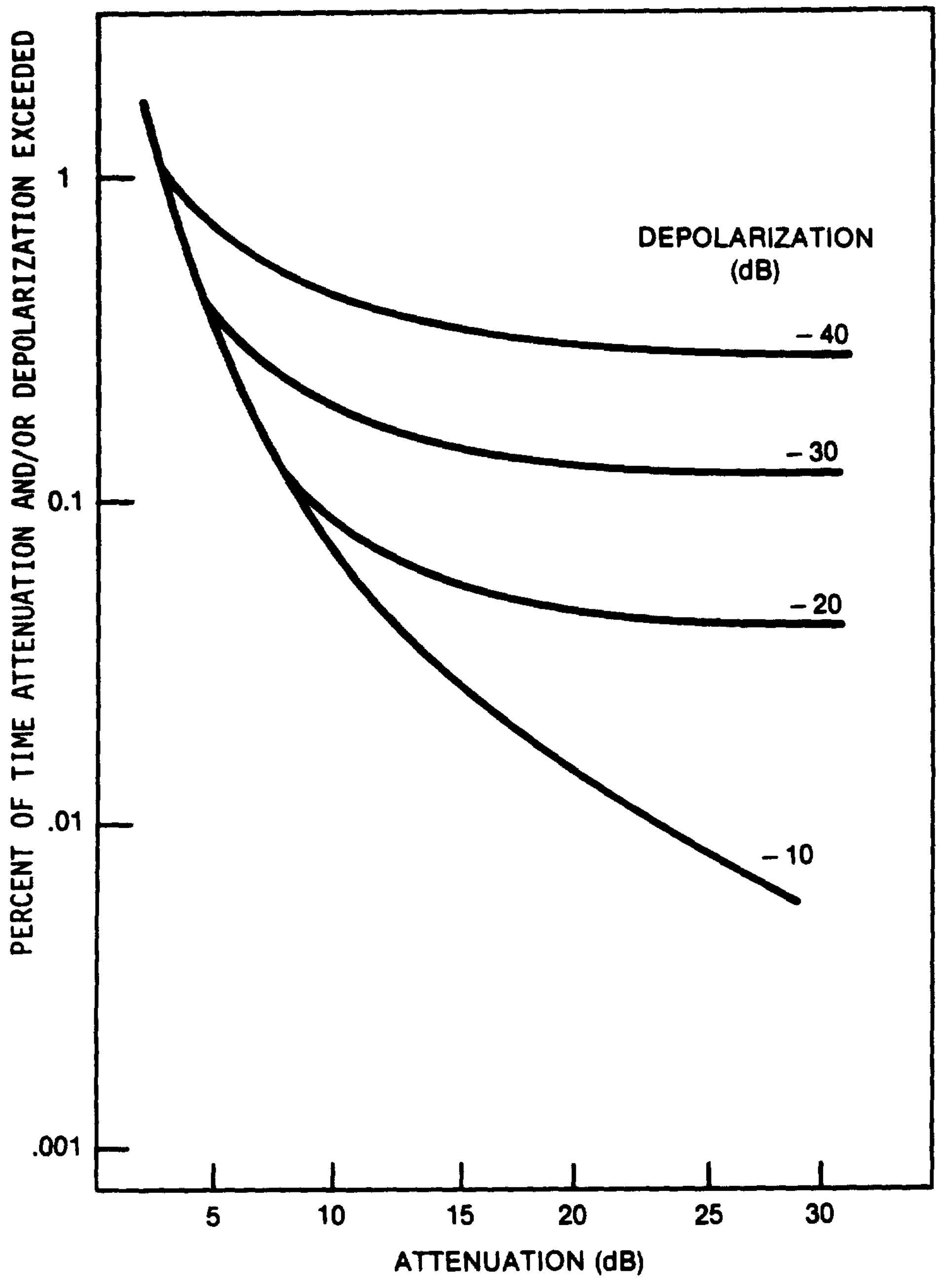

Figure 7.3-4. Composite Outage Versus Attenuation with Depolarization as a Parameter (Hypothetical Case)

into the attenuation only curve. Only this curved portion involves estimation by eye, and will introduce negligible error for initial design purposes.

The effect of diversity in reducing depolarization outage has received little attention to date (see Wallace-1981). The procedure outlined above applies to single-terminal attenuation and depolarization. When outages from attenuation and depolarization are each of the same order of magnitude, it is not clear that the concept of diversity gain (Section 7.4.1) is appropriate, since diversity should reduce depolarization outages as well.

In contrast to the "outage" values of depolarization, the smaller but more frequent values of depolarization can be accommodated in the system power margins. In almost all satellite communications systems, the thermal noise is the dominant portion of the total noise and interference. Small cross-polarized components may therefore be treated like any other interference. Castel and Bostian (1979) point out that depolarization on digital systems can be regarded as an equivalent C/N degradation. The equivalent degradation D due to depolarization for a n-ary PSK system is bounded by

$$D(\text{db}) < -20 \log \left[1-(\log^{-1} x/20)/\sin(\pi/n)\right] \qquad (7.3\text{-}5)$$

where x is minus the cross polarization discrimination (XPD), in decibels. The effect of crosspolarization (and interference in general) on digital systems is considered more precisely by Rosenbaum (1970) and Rosenbaum and Glave (1974). The determination of link availability considering the equivalent degradation in combination with rain attenuation is discussed by Wallace (1981).

Similar procedures apply in analog systems. In practice, the equivalent noise powers from all thermal noise and interference sources, including intermodulation and depolarization, are added together, in pW0p for example, to produce a total link noise power